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THE MINERAL MATTER OF THE SEA, WITH SOME SPECULATIONS AS TO THE CHANGES WHICH HAVE BEEN INVOLVED IN ITS PRODUCTION

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It has been calculated that if the salt now in the sea were precipitated, it would make something like 3,500,000 cubic miles. If to this be added all the other mineral matter in solution in the sea water, the amount would be swollen to about 4,500,000 cubic miles.[1] This amount of mineral matter is equal in amount to nearly one-fifth of all the material in all lands above the sea at the present time; that is, equal to all the material in North America, Europe, and Australia, and most of the islands of the sea. If the mineral matter of the sea were precipitated on the ocean bottom, it would make a layer about 175 feet deep. If it were precipitated and concentrated in the shallow water of the ocean about the borders of the continents, building up the bottom to sea-level, this amount of mineral matter would add something like 19,000,000 square miles to the land—an area equal to about one-third that of all existing land. Most of this mineral matter in solution in the sea has probably come from the rocks of the land and of the sea bottom, chiefly the former.

Amount of mineral matter extracted from the sea.—These figures may perhaps give some idea of the amount of mineral matter in solution in the sea, but they give no more than a hint of the importance

[1] *Scottish Geographical Magazine*, Vol. XXI, p. 133.

of the solvent work of water, for most mineral matters carried to the sea in solution by rivers are extracted from the water about as rapidly as they are supplied. It is probable, indeed, that the amount of mineral matter which has been extracted from the sea water far exceeds all that remains in solution. This conclusion may be reached either (1) by calculating the volume of rock material which has been extracted from the sea water, or (2) by comparing the proportions of the various sorts of mineral matter in sea and in river water.

1. The rock matter extracted from the sea includes most of the limestone, the gypsum, and the salt, and much of the cementing material of all other sorts of sedimentary rock. Data concerning the thickness of such materials beneath the sea are not available, but some calculations concerning their average thickness in land areas, most of which have been beneath the sea at times, have been made. Dana estimated the average thickness of limestone (presumably for the continents) at about 1,000 feet.[1] This figure appears to take no account of the calcium carbonate which forms an important constituent of many shales and some sandstones, and it is not clear whether it was meant to include dolomites.

Reade estimates the thickness of the limestones for the globe (not for the continents merely) at about 528 feet;[2] but this figure, like the preceding, appears to take no account of the calcium carbonate in the sandstones and shales.

Van Hise, attempting to underestimate rather than overestimate, assigns a thickness of 328 feet to the limestones of the continents in the zone of katamorphism, and estimates that about an equal amount of calcium carbonate exists in the shales and sandstones.[3] This gives an aggregate of 656 feet of calcium carbonate for the continents above the zone of anamorphism.

If the estimates of Dana and Reade be increased to make allowance for the calcium carbonate in the shales and sandstones, and if the estimate of Van Hise be increased to include the limestones below

[1] Dana, *Manual of Geology*, 4th ed., p. 485.

[2] T. Mellard Reade, *Chemical Denudation in Relation to Geological Time* (London, 1879), p. 53.

[3] *Monograph 47*, U. S. Geological Survey, pp. 940, 941.

the zone of katamorphism—and limestone is known to exist there—all the above figures will be increased.

No careful estimate of the amount of limestone beneath the sea is possible, but its amount must be great. It probably forms a larger proportion of the sediment than on land, but it does not follow that its average thickness is greater. If we assume that the average thickness of limestone beneath the sea is half as great as that on the land, and that the amount of calcium carbonate in other sedimentary rocks beneath the sea is, on the average, half as great per square mile as on land, we may derive from the figures representing the estimated thickness of limestone material on the continents, figures representing an estimated average for the earth. These figures are 420 (based on the estimate of Van Hise) and 850 feet (based on the estimate of Dana). The estimate of Reade, increased to allow for the calcium carbonate in clastic rocks, becomes 738 feet.

Even if these large figures be correct, they represent less than the total amount of mineral matter which has been extracted from the sea, since they deal with one sort of mineral matter only. How much they should be increased to include all the mineral matter ever extracted from the waters of the sea cannot be stated; but the silica, the various sulphides and sulphates, the chlorides, etc., which have been extracted from the sea water, would swell them appreciably.

Much material, such as that of limestone, has been extracted from the sea water and deposited, and then re-dissolved, re-extracted, and re-deposited. Some material, indeed, has probably gone through this cycle many times. The aggregate result of the solvent work of water is therefore not represented by the amount of existing rock matter which has been extracted from the sea, plus that which still remains in solution. Furthermore, the considerations adduced take no account of the deposition of material from solution on the surface of the land, or beneath it, or in the lithosphere under the sea. The amount of mineral matter deposited from solution in these situations is certainly great, though it cannot well be estimated. It must, however, be recognized, in attempting to gain the proper conception of the solvent work of ground water.

2. By comparing the mineral matter in the sea water with that in average river water, Tables I and II, it is seen that calcium car-

bonate is about 20 times as abundant as sodium chloride in river water, but only $\frac{1}{225}$ as abundant in sea water. If the calcium carbonate which has been taken to the sea in solution by rivers had remained in solution as calcium carbonate in the same proportion that the sodium chloride has remained in the sea water, the figures representing the amount of common salt which the sea contains would seem almost insignificant in comparison. Even if calcium carbonate is changed to calcium sulphate in the sea, as is sometimes thought, the case is not seriously altered, for the amount of calcium sulphate in the sea is but a small fraction of the amount of sodium chloride. In order that the sodium chloride should have attained such predominance, it is necessary to suppose that enormous quantities of the compounds of calcium have been extracted, if the salt of the sea has been derived from the land.

The average river water contains about seven times as much magnesium carbonate as sodium chloride, four and a half times as much silica, twice as much calcium sulphate, twice as much sodium sulphate, more potassium sulphate, and more sodium nitrate; yet the combined volume of all these substances in the sea water is but a small fraction of the amount of sodium chloride.

By either of these lines [(1) and (2)] of approach, we reach the conclusion that the amount of mineral matter which the sea has lost from solution far exceeds that which it has held until the present time.

TABLE I

AMOUNT OF MINERAL MATTER IN SOLUTION IN ONE CUBIC MILE OF SEA WATER[1]

Constituents	Tons
Chloride of sodium ($NaCl$)	117,434,000
Chloride of magnesium ($MgCl_2$)	16,428,000
Sulphate of magnesium ($MgSO_4$)	7,154,000
Sulphate of calcium ($CaSO_4$)	5,437,000
Sulphate of potassium (K_2SO_4)	3,723,000
Bromide of magnesium ($MgBr_2$)	328,000
Carbonate of calcium ($CaCO_3$)	521,000
For sea water, total dissolved matter	151,025,000

[1] Dittmar, *Challenger Reports*, Physics and Chemistry, Vol. I, p. 204.

TABLE II

MINERAL MATTER IN SOLUTION IN ONE CUBIC MILE OF AVERAGE RIVER WATER[1]

Constituents	Tons
Calcium carbonate ($CaCO_3$)	326,710
Magnesium carbonate ($MgCO_3$)	112,870
Calcium phosphate ($Ca_3P_2O_8$)	2,913
Calcium-sulphate ($CaSO_4$)	34,361
Sodium sulphate (Na_2SO_4)	31,805
Potassium sulphate (K_2SO_4)	20,358
Sodium nitrate ($NaNO_3$)	26,800
Sodium chloride ($NaCl$)	16,657
Lithium chloride ($LiCl$)	2,462
Ammonium chloride (NH_4Cl)	1,030
Silica (SiO_2)	74,577
Ferric oxide (Fe_2O_3)	13,006
Alumina (Al_2O_3)	14,315
Manganese oxide (Mn_2O_3)	5,703
Organic matter	79,020
Total dissolved matter	762,587

Time necessary for the accumulation of the mineral matter of the sea.[2]—The discharge of water into the sea by rivers is estimated at 6,524 cubic miles per year.[3] This volume of water is estimated to carry to the sea 0.433 cubic miles of mineral matter in solution.[4] At this rate, it would take about 10,500,000 years for the streams to carry to the sea an amount of mineral matter equal to that which it now contains, and at this rate it would take about 54,000,000 years for an amount of mineral matter equal to all that is now above the sea, to be dissolved and carried to the oceans.

The sodium chloride makes up about 2.2 per cent. of the mineral matter in solution in river water. The same substance constitutes nearly 78 per cent. (77.758 per cent.) of the mineral matter in the sea water. The 2.2 per cent. of 0.433 cubic miles is 0.0095 of one cubic

1 Murray, *Scottish Geographical Magazine*, Vol. III, p. 77.

2 Most of the following computations have been made or verified by Messrs. J. H. Lees and E. W. Shaw.

3 Murray, *op. cit.*, Vol. IV, p. 41.

4 Murray, *loc. cit.*, states that the amount of mineral matter carried to the sea annually by rivers is 1.183 cubic miles; but the data on which this calculation is based (*op. cit.*, Vol. III, p. 76, 77) give only 0.433 cubic miles.

mile, which represents approximately the amount of salt brought to the sea per year by rivers, assuming that the specific gravity of salt is the same as the average specific gravity of the mineral matter in solution in the sea and rivers; while 77.758 per cent. of the total amount of mineral matter of the sea (4,532,110 cubic miles) is 3,524,-078 cubic miles, the approximate amount of salt in solution in the sea water. This amount divided by 0.0095 is more than 370,000,000, which represents roughly the number of years it would take for the amount of salt now in the sea to have been brought to it by rivers, at the present rate.

This figure is, however, not to be taken as representing the age of the sea. There are several reasons for avoiding this conclusion. These are as follows: (1) The rate at which salt has been brought in by rivers has probably not been constant; (2) the salt may have been derived partly from sources other than land waters; and (3) much salt has been extracted from the sea water and deposited. The second and third points tend to offset each other. In spite of the limitations imposed by these considerations, the figure 370,000,000 may give some conception of the order of magnitude of the number which expresses the age of the sea in years.[1]

The calcium carbonate carried to the sea by rivers in solution, at the present time constitutes, according to Table II, nearly 43 per cent. of all the mineral matter taken to the sea in solution. Its amount is therefore about one-fifth of a cubic mile per year. The calcium carbonate now in solution in sea water represents but 0.00345 of the mineral matter which the sea contains. This fraction of 4,532,110 cubic miles is about 15,635 cubic miles, which represents, approximately, the amount of calcium carbonate now in solution in the sea. If this substance is carried to the sea at the rate of one-fifth of a cubic mile per year, it would take only about 84,000 years for the amount now in solution in the sea to be brought down from the land. If the calcium sulphate of the sea water has been derived partly from the calcium carbonate brought to the sea, this

[1] Professor Joly has calculated, from the salt of the sea, that the time since the ocean began to receive solutions from the land may be 90 to 100 millions of years. He assigns 10 per cent. of the sodium chloride of the rivers to atmospheric sources. (*Transactions of the Royal Society of Dublin*, Vol. VII (Series 11), 1899, p. 23, and *Geological Magazine*, 1900, p. 220.)

period of 84,000 years should be lengthened. Treating calcium carbonate and calcium sulphate as one, it would take the rivers about 740,000 years to contribute what the sea now contains.

The reason for the great discrepancy between these figures and those which represent the time necessary for the accumulation of the salt of the sea, is doubtless found in the fact that the calcium compounds are extracted by the organisms of the sea, to make shells, tests, etc., about as fast as they are brought in, while the salt remains in solution.

The amount of calcium carbonate which may have been in solution in the sea.—The amount of calcium carbonate which would have been carried to the sea by rivers in 370,000,000 years, at the rate at which rivers are now contributing it, is about 68,600,000 cubic miles. In the same time the rivers should, at their present rate, have contributed about 7,200,000 cubic miles of calcium sulphate, or nearly 76,000,000 cubic miles of calcium carbonate and calcium sulphate. Since not more than about 179,000 cubic miles of calcium compounds (carbonates and sulphates) remain in solution in the sea at the present time, it will be seen that an enormous amount must have been extracted.

Most of the calcium deposited in the sea has been deposited in the form of calcium carbonate. If an amount of calcium carbonate and calcium sulphate corresponding to the difference between 76,000,000 and 179,000 cubic miles has been deposited, it would make a layer about 1,920 feet thick over the entire earth. Since, however, some of the calcium carbonate taken in solution to the sea has been redissolved, some of it repeatedly, after precipitation, the average thickness of that which has been deposited must be much less than 1,920 feet. Perhaps this figure should be reduced by one-half on this account.

Sixty-eight million six hundred thousand cubic miles, it may be noted, is about three times the cubic contents of all lands. Assuming that rivers have been supplying calcium carbonate and sodium chloride to the sea at the present rate, and assuming that the land has been the only source of these materials in the sea, it follows that the rivers should have carried to the sea an amount of calcium carbonate equivalent to about three times the cubic contents of all exist-

ing land, during the time necessary for furnishing the salt, at the present rate. If some of the salt has been derived from the lithosphere beneath the sea, the figures should be correspondingly reduced, though it is probable that the land has furnished much more salt than the sea bottom has. The reduction on this account is, in some measure, or perhaps altogether, offset by the allowance which should be made in the opposite direction for the salt which has been deposited among the sedimentary rocks of the earth.

Amount of average rock decomposed.—From the amount of salt in the sea, and from the amount of calcium carbonate which the sea is estimated to have had, calculations may be made as to the amount of average rock which must have been destroyed to produce them.

1. The average composition of accessible non-sedimentary rocks has been determined, probably with a fair degree of accuracy.[1] Knowing the percentage of sodium in this average rock, the volume of rock which must have been decomposed in order to furnish the sodium necessary to make the salt of the sea may be calculated. The average rock contains about 2.53 per cent. of sodium, and of rock containing this amount of sodium nearly 55,000,000 cubic miles would need to be decomposed, to yield enough sodium to form the salt now in the sea. The salt of the sea, therefore, seems to imply the decomposition of some such quantity of average rock. Since only about 23,500,000 cubic miles of rock now remain above sea-level,[2] and since much of this is sedimentary rock derived from the original rock, and since much of the non-sedimentary rock is not decayed, and still holds its sodium, it would appear that the larger part of the 55,000,000 cubic miles of rock necessary to yield the requisite amount of sodium must have been removed from the land to the sea.

2. A similar line of inquiry may be based on the amount of calcium carbonate which the sea has had in solution. The average rock contains about 4.90 per cent. of CaO.[3] On p. 471 the figures 420, 738, and 850 feet were deduced as perhaps representing, as well as they are now known, the limiting average thicknesses of limestone material for the earth. The largest of these figures is about twice

[1] F. W. Clark, *Bulletins 168* and *228*, U. S. Geological Survey.

[2] Murray, *op. cit.*, Vol. IV, p. 40. [3] Clark, *op. cit.*

the smallest. For convenience of calculation, and in view of the somewhat uncertain nature of the data on which they are based, no further error of great magnitude will be involved if the smallest of these figures be regarded as half of the largest, that is, 425.

If 425 and 850 feet be assumed to represent the maximum and minimum average thickness of limestone material, as nearly as it is now known, and if four-fifths of this be assumed to be calcium carbonate,[1] the amounts of calcium carbonate in the earth's crust would be equivalent to nearly 12,700,000 cubic miles in the one case, and to 25,400,000 cubic miles in the other. These figures are much smaller than that given on p. 475, but that includes the calcium carbonate re-dissolved, and carried anew to the sea, after being once deposited. These do not.

The amounts of average rock the decomposition of which would be needed to yield the amount of calcium necessary for these amounts of calcium carbonate, supposing all the calcium to be separated so as to be available for union with carbonic acid gas, would be 145,000,000 cubic miles and 290,000,000 cubic miles, respectively. These results, it will be seen, are about 2.6 and 5.2 times as large, respectively, as those derived from the calculation based on salt of the sea. Even after allowance is made for the salt which has been deposited, the figures are far apart. This means that some of the sodium does not unite with chlorine to produce salt, or that more of the sodium chloride has been deposited than is known, or that there is some other discrepancy in the data. In spite of the discrepancy, however, it will be noted that the figures belong to the same order of magnitude.

The same problem may be approached in another way. We have seen that the amount of calcium carbonate which should have been carried to the sea in the time necessary for the accumulation of the salt, assuming all of the latter to have come from the land, and at the present rate, is more than 68,000,000 cubic miles, and, if the calcium sulphate be added, about 76,000,000 cubic miles. To yield the calcium called for by these volumes, the decomposition of about 777,000,000 cubic miles of average rock would be necessary, if the calcium carbonate only is taken into consideration, and more than 60,000,000

[1] The rest being magnesium carbonate. Clark, *Bulletin 228*, U. S. Geological Survey, pp. 20, 21.

cubic miles more, if the calcium sulphate be included. Seven hundred and seventy-seven million cubic miles is more than 33 times the estimated cubic contents of the land, while 837,000,000 cubic miles (777,000,000 + 60,000,000) is about 36 times the estimated cubic contents of the land. These figures should be reduced to make allowance for the calcium carbonate which has been redissolved after having been precipitated. If half the calcium carbonate which the ocean water has had has been re-dissolved after having been once precipitated, the last figures should be divided by 2. Reduction should also be made for the calcium carbonate which has been derived from the rocks beneath the sea.

Assuming that 2 is the proper divisor, the amount of average igneous rock which must have been destroyed to produce the amount of calcium carbonate carried to the sea, at the present rate, in 370,000,000 years, is about 388,500,000 cubic miles, or, if calcium sulphate be included, 418,500,000 cubic miles. This amount of rock would make a layer more than 2 miles thick over the entire surface of the earth, and more than 6½ miles thick over the continents and continental shelves. This volume of mineral matter is about 18 times all that is now above the surface of the sea. These calculations, even though the figures involve a considerable error, indicate that an enormous body of rock must have been decomposed.

By both these methods of calculation, based on the calcium carbonate, it will be seen that the amount of average rock needed (pp. 476 and 477) to yield the estimated supply of calcium carbonate is considerably more than that needed to yield the known amount of salt. It is probable that salt furnishes the better basis for the estimates, since the amount which has been formed is probably more nearly known, most of it being presumed to still remain in the sea.

Even the above figures do not represent the full measure of transfer of the material from land to sea. In the decomposition which igneous rock undergoes, before yielding up its calcium in soluble form, it undergoes notable expansion. It follows that the preceding figures great as they are, may not represent the actual amount of average rock material destroyed, and removed from land to sea.

Assigning the average igneous rock a mineral constitution consistent with its chemical composition, its expansion on decomposition

may be estimated. The precise changes which such rock undergoes doubtless vary from point to point, and the degree of change before removal by erosion must also vary. It is probably safe to say that if the decomposition is measurably complete, the expansion in volume would be not less than an eighth, and it might be as much as a third. Let it be assumed to be one-fifth. The 55,000,000 cubic miles, the decomposition of which is called for to furnish the sodium necessary for the salt of the sea, would then become 66,000,000 cubic miles, and the 145,000,000 and the 290,000,000 cubic miles, the decomposition of which is called for to furnish the calculated amount of calcium carbonate, would become, respectively, about 174,000,000 and 348,000,000 cubic miles; while the 388,500,000 and 418,500,000 cubic miles (p. 479), increased by one-fifth, become about 466,000,000 and 502,000,000 cubic miles, respectively. These figures represent, respectively, about 3, 7, 14, 20, and 21 times the amount of material now above sea-level.

Since most of the decomposed rock is believed to have been in the land, and since but about 23,500,000 cubic miles now remain above sea-level, and this largely undecomposed, so far as it is nonsedimentary, it follows that an enormous body of rock material must have been removed from the land to the sea. If the rock so removed was not so completely decomposed as to yield up all its sodium and calcium, the total amount would have been greater than if decomposition were complete. When due allowance is made for the uncertainties of these figures, they are still so large as to give a magnified conception of the work which land waters may have done in the later stages of the earth's history. The transfer from land to sea of an amount of material equal to even 3 times all that that is now above the sea is most impressive. The transfer of an amount 21 times as great as that now above the sea, is still more stupendous.

3. The same general results may be approached in another way, though the calculation is based on somewhat speculative data. It has been estimated that the carbonic acid gas of the atmosphere is being consumed, in the original carbonation of rocks, at the rate of 270,000,000 tons per year.[1] On the assumption that four-fifths of this amount of carbonic acid gas goes to the carbonation of calcium

[1] Reade, cited by Chamberlin, *Journal of Geology*, Vol. VII, p. 682.

oxide,[1] the amount of calcium carbonate produced would be about 490,900,000 tons per year. This would make approximately $\frac{1}{26}$ of a cubic mile. To furnish the amount of calcium oxide necessary for this amount of calcium carbonate, the decomposition of nearly one-half (0.44) a cubic mile of average rock would be required. In 370,000,000 years (p. 474) some 163,000,000 cubic miles of average rock would have been decomposed at this rate.

4. We are not obliged to rely on calculations based on somewhat unobtrusive changes, for our knowledge of the wasting away of the continents. Some conception of its importance may be gained in another way. The amount of sediment which streams carry to the sea each year has been calculated, with some approximation to accuracy. The amount of matter which they take to the sea from the land, including that carried in solution, as well as that carried mechanically, has been estimated as 3.7 cubic miles every year.[2] If this figure be modified to make allowance for the reduced volume in solution (p. 473), it becomes a little less than 3 cubic miles (2.93). Besides this loss to the lands through the erosion of the rivers, the winds blow great quantities of dust and sand into the sea every year, while the waves beat effectively on the coasts, cutting off, in the aggregate, enormous quantities of land material, and extending the dominion of the sea.

If rivers were to continue to wash away the continents at the present rate, they would remove to the sea an amount of material equal to all that is now above sea-level in less than 8,000,000 years, and the work of the winds and waves would shorten this period considerably.

If rivers have been wasting the land at the present rate for 370,000,000 years, they would have destroyed and carried away from the land about 58 times the amount of rock material now above sea-level. These figures take no account of the material blown from the land to the sea, nor of that worn from the shores by waves. If the work of these agents were taken into consideration, the figures given above would be notably increased. On the other hand, the

[1] F. W. Clark, has shown that the ratio of calcium oxide and magnesium oxide in 345 limestones analyzed is about 5½ to 1. *Bulletin 228*, U. S. Geological Survey, pp. 20, 21.

[2] Murray, *op. cit.*, Vol. IV, p. 41.

present rate of river erosion is probably well above the average for the earth's history, since the lands are now relatively high.

5. There is still another way of approaching this problem. The sedimentary rocks of the continental areas are estimated to have a thickness, on the average, of something like a mile. No estimate of their average thickness in the sea is possible, but it is probably much less. If it be assumed to be one-fourth as great, the volume of sediment for the whole earth would be about 4 times that of the rock in all the lands of the earth. These figures, it will be seen, are near the least of those derived by the other modes of calculation (see p. 479).

Summary.—It appears, then, that we are to think of the decay and removal to the sea of an amount of rock equal to at least several times all that is now above the sea, during the course of the earth's history. The results of the several lines of calculation place the amount at 3 to 21 times all that is now above sea-level. The truth may lie between these extremes. So uncertain is the nature of the data, however, that we must recognize that the truth may lie outside of either, so far as present knowledge goes.

Renewal of the continents.—It is, of course, not to be inferred that the continents were ever large enough to include all the material which has been worn away from them, in addition to that which they now contain. They may never have been much larger than now, and they have certainly often been smaller. As their masses were reduced by erosion, they were renewed, either (1) by the sinking of the sea bottom, which drew the water off the areas which had been covered by shallow water only, or (2) by the rise of the continental areas. The former was probably the more common.

The renewal of the lands has not always kept pace with their reduction, so that the area of the lands and the amount of rock which they have contained, have fluctuated notably from time to time.

Effect of preceding changes on areas of sea and land.—Though great weight is not to be attached to the figures worked out on the basis of the assumptions made, it is believed not only that they are suggestive of the amounts of rock which have been worked over in the earth's history, but that they suggest lines of quantitative study which are worthy of attention. If, for example, a given amount of

rock has been removed from land to sea, the resulting change of sea-level may be calculated. If the bottom of the sea were not warped so as to increase or decrease the capacity of its basin, the transfer of 66,000,000 cubic miles of rock from land to sea would raise the level of the latter more than 2,400 feet,[1] if no allowance be made for the increased area resulting from the rise. The transfer of 174,000,000 cubic miles of rock from land to sea would raise its level more than 6,400 feet, while the transfer of 348,000,000 cubic miles would raise its level nearly 13,000 feet, or more than two and one-half miles, if its area remained constant. The increase of area which would be involved would, of course, reduce these figures sensibly.

If the sea-level were to rise 2,400 feet at the present time, about two-thirds of all the present land would be submerged, and if it were to rise 13,000 feet, only about 2 per cent. of the present land would remain above it. Even if allowance is made for the increase of area which its rise would produce, the transfer of 348,000,000 cubic miles of rock material to the sea would leave no vestige of land in North America east of the Rocky Mountains, and all that remained within the area of the western mountains would be a series of islands where the higher mountains now are. On the basis of even the least of these figures, 2,400 feet, reduced so as to make allowance for the increase of area which would be involved, there would be changes of relative level between sea and land, of an order commensurate with those which are known to have taken place from time to time during the earth's history.

There is reason to believe that the continents, at least those whose geological history is best known, have more than once been worn down toward sea-level—worn down so low that rivers became sluggish, and their mechanical erosion relatively slight. Such a condition would exist if the lands of the present time were worn down to an average height of 500 feet. In this case, about 5,000,000 cubic miles

[1] The materials taken to the sea in solution would not raise the level of the sea so much, cubic mile for cubic mile, as mechanical sediments. Since much the larger part of the sediment taken to the sea has been in the form of mechanical sediments, if we may judge from present conditions, this difference is here neglected; but it seems probable that the amount of dissolved matter has been greater than now, relative to the mechanical sediments, if the whole of the earth's history be considered.

of rock would remain above sea-level, while about 17,000,000 would have been removed. The deposition of 17,000,000 cubic miles of mineral matter in the sea would raise its level between 500 and 600 feet, and such a rise would submerge an area of about 12,000,000 square miles of the present land, or more than one-fifth of its area. Considering the much larger area which would be submerged by an equal rise of the sea-level when the lands had been lowered to the extent indicated, there would be a submergence of continents comparable to those which have repeatedly marked the beginnings and ends of geologic periods.

The facts (1) that the notable changes in relative level of land and sea have been periodic, and (2) that the sea-level seems to have been lowered at times, and not to have been continually rising, as it would be if affected by sedimentation alone, are probably to be accounted for by crustal warpings.

In so far as sedimentation has been a cause of subsidence of the ocean bed, the subsidence has probably lagged behind the sedimentation. In so far as the sinking of the sea bottom is independent of sedimentation, it is unlikely that it always, or even generally, kept pace with sedimentation. It would appear, therefore, that rise of the sea-level due to sedimentation may have been an important factor, or even, perhaps, a chief factor, in the submergence of the continents, at various periods in the earth's history, while the unequal rates at which sediment has been transferred from land to sea may have had an influence on the rate at which submergence was brought about. It is highly probable that crustal warpings, by increasing the capacity of ocean basins, have, on the whole, tended to reduce the amount of change of sea-level which sedimentation alone would have effected. Volcanic material extruded into the sea, on the other hand, has worked in the opposite direction.

Rate of change in relations of sea and land.—It is not to be supposed that such changes in the level of the sea as those mentioned on p. 482 have actually taken place as the result of sedimentation, for the ocean bed has probably been sinking through the ages, though perhaps not continuously, and probably not at a constant rate, even during periods of sinking. Subsidence of the ocean bottom would tend to counteract the effect of sedimentation, so far as its effect on

the level of the sea is concerned, for sinking of the bottom increases the capacity of the basin, just as the deposition of sediment in it decreases it. At those periods when sedimentation in the oceans exceeded subsidence of the ocean beds, the sea-level must have risen, and the lower parts of the continents must have been submerged. At those periods when subsidence of the ocean bed increased the capacity of the basin more rapidly than sedimentation decreased it, the water would have been drawn off the continental shelves, and lands would have emerged. It seems not improbable that this has been a main factor in bringing about repeatedly the submergences of great parts of the continental areas, in the course of geological history.[1] The periodic sinking of the continents bodily has doubtless also been a factor leading to the same result.

It is to be understood that all changes of sea-level, due to sedimentation and warping, have probably taken place very slowly—so slowly that their effects, in all probability, would not have been conspicuous to observers, had there been observers to witness them.

[1] The effectiveness of gradation (degradation and aggradation) in bringing about considerable submergences of land areas was first urged, so far as I am aware, by Professor Chamberlin.